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TREATMENT OF BRACKISH, SEA AND CHEMICALLY CONTAMINATED
FRESH WATER BY REVERSE OSMOSIS

By Robert P. Carnahan¹, M. ASCE, A. Roger Anzzolin² and Robert G. Ross²

As a result of ten years of extensive research and development, the US Army has developed a prototype, trailer-mounted reverse osmosis water purification unit which effectively treats brackish water, sea water, and chemically contaminated freshwater. The treatment processes consist of high rate filtration with direct application of polymer followed by filtration with a 5-micron cartridge filter and then the reverse osmosis system. Under the present concept there will be two sizes of units under development; one will produce 600 gallons per hour and the other unit will produce 3000 gallons per hour of potable water from a fresh or brackish water source.

Two of the 600 gallon per hour units have completed over 2000 hours of engineering testing at Aberdeen Proving Ground, MD; Fort Cragg, NC; and Eglin Air Force Base, FL. Results of this testing demonstrated that reverse osmosis is a versatile treatment process which can meet the US Army's requirements for producing water in a combat environment.

Design and Description of Equipment

This equipment was designed to operate for 20 hours a day at a production rate equivalent to 600 gallons per hour on freshwater and 400 gallons per hour on sea water. Since the equipment was required to be air transportable, the size was restricted to 250 inches in length, 96 inches in width, and 100 inches in height which includes space for a generator. A weight limitation of 18,000 pounds was established, which permits airdropping the unit by parachute, lifting it by helicopter and towing it behind a 2 1/2 ton truck. Because of parachute delivery, the entire system had to be designed to withstand a deceleration force of 24 g's. A climatic requirement to operate at temperatures ranging between 35°F and 105°F at relative humidities as high as 90 percent was established to provide a world wide operational capability.

The water quality standards which the product water had to meet are established by the US Army Surgeon General. A summary of these field standards is given in Table I. For fixed installations, the standards are the same as the EPA 1975 interim primary drinking water standards.

¹ Development Project Officer for the Reverse Osmosis Program, USAMERADCOM (ORDME-GS), Fort Belvoir, VA.

² Development Project Engineer, Reverse Osmosis Program, USAMERADCOM (ORDME-GS), Fort Belvoir, VA.

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TABLE 1 - Treated Water Quality Standards⁽¹⁾

Constituents	Field Supplies	
	Short Term (Less Than 7 Days)	Long Term (More Than 7 Days)
PHYSICAL:		
Color		50 Units
Turbidity	Reasonably Clear	5 Units
CHEMICAL:		
Arsenic	2 mg/l	0.2 mg/l
Chloride		600 mg/l
Cyanide	20 mg/l	2 mg/l
Magnesium		150 mg/l
Sulfate (SO ₄)		400 mg/l
Total Dissolved Solids		1500 mg/l
CHEMICAL WARFARE AGENTS:		
Hydrogen Cyanide	20 mg/l	2.0 mg/l
Lewisite	2.0 mg/l	0.2 mg/l
Mustard	2.0 mg/l	2.0 mg/l
Nerve Agents	0.02 mg/l	
RADIOLOGICAL:		
Gross Beta Activity		1000 pc/l*
Strontium 90		10 pc/l
Radium 226		3 pc/l

* 1962 PHS drinking water standards for Fixed Installations.

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A review of commercially available reverse osmosis systems showed that no system was available that would meet the Army's criteria. Therefore, a concept design, Figure 1, was developed using modified commercially available components. After completing the design and procuring the components, the Mobility Equipment Research and Development Command awarded a contract for the detailed design and fabrication of two prototype units as shown in Figure 2.

The design was divided into two elements: a pretreatment system, and a reverse osmosis system. The pretreatment system consists of the raw water pumps, chemical feed, and filtration equipment, while the reverse osmosis system consists of the high pressure pump, reverse osmosis components and potable water distribution system.

Design of the raw water pumping system was based on a maximum total head of 240 feet. This was predicted on having a filter operating pressure of 30 psi, a head loss through the system of 110 feet, and a static head of 60 feet. Since a 30 gallon per minute (gpm) two stage pump was too heavy to move to the water source, two single-stage, self-priming centrifugal pumps were selected. This also provided standby capability when the total head did not exceed 120 feet. To prevent corrosion, aluminum bronze volutes and impellers were specified. The intake consisted of 30 feet of 1 1/2 inch diameter hard rubber hose, a float and strainer with suction lift limited to 10 feet. Seventy-five feet of 1 1/2 inch diameter canvas hose was used as the raw water conduit.

The chemical feed system was designed to provide a mean velocity gradients of 300 sec^{-1} for approximately one tenth of a second and of 800 sec^{-1} for two seconds. Preliminary testing showed that this provided adequate mixing without adversely affecting coagulation. An American Lewa positive displacement metering pump was selected to feed the cationic polymer (CAT FLOC T-1), the sodium hexametaphosphate, the calcium hypochlorite and the citric acid.

Since the water purification system had to fit within a frame 114 inches long by 96 inches wide and 66 inches high, conventional clarification systems could not be used. Therefore, direct filtration was used. After sizing and testing several filters, both commercial and fabricated, a modified 30-inch diameter Culligan Quadra-kleen filter was selected because its performance approximated closely the design criteria. It has a bed 30 inches deep, consisting of anthracite, sand, garnet and support media, and was designed to operate at rates of 5 to 10 gallons per minute per square foot (gpm/sf). This provides the optimum in trade off in size versus filtration efficiency. The Culligan filter also has an automatic backwash cycle which operates at two rates, 14 and 24 gpm/sf, and which fully fluidizes the bed. The filter shell and underdrain system were modified to withstand the shock of air drops.

Six, thirty-inch filter cartridges were used after the multi-media filter to prevent carry-over of solids during conditioning of the multi-media filter. Experience has shown that any carry-over of solids has a detrimental effect on the performance of the reverse osmosis membrane.

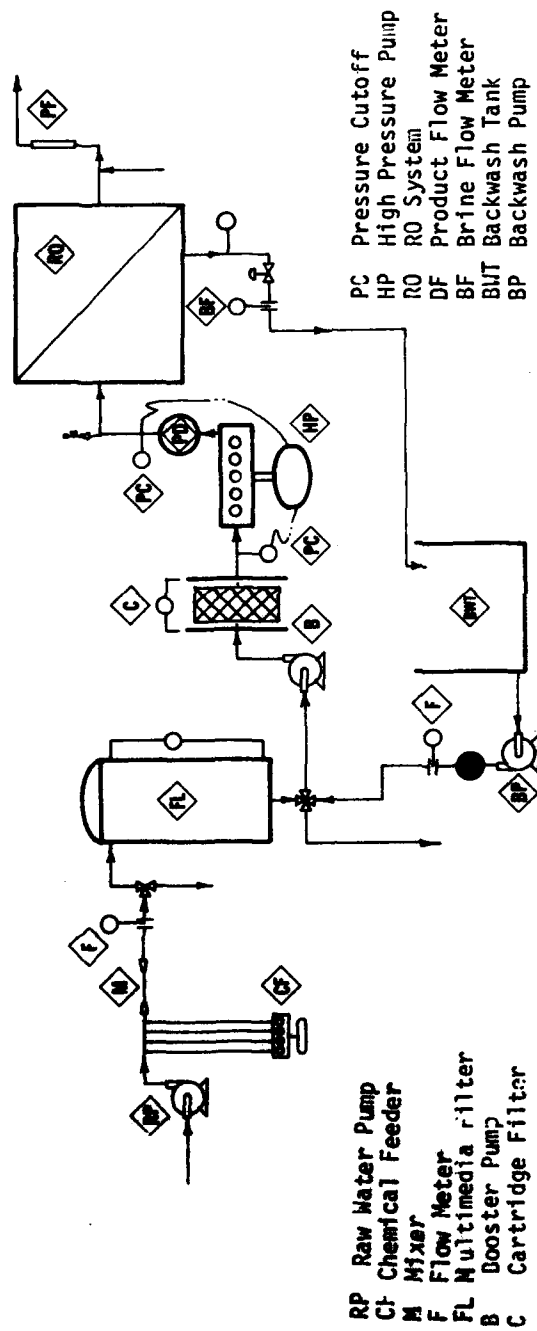


Figure 1. FlowSheet of 600 GPH Reverse Osmosis Water Purification Unit.



Figure 2. Prototype Model of 600 GPH Reverse Osmosis Water Purification Unit.

Of particular concern was carry over of organics; therefore, the carbon impregnated five micron cartridges were used.

The high pressure pumping system consists of an aluminum bronze quintuplex positive displacement pump, pulsation dampener, high and low pressure cut off switches, pressure relief valve, and rupture disk. Since it was necessary to maintain a constant flow through the membranes regardless of pressure, a positive displacement pump was selected rather than a centrifugal pump. It also had a functional advantage as a rate of flow controller for the filter. The pump was sized to deliver a flow of 30 gpm at a maximum discharge pressure of 980 pounds per square inch (psi). To compensate for acceleration head on the inlet side of the pump, the booster pump and cartridge filter system were sized to provide a flooded inlet and a positive head of 10 psig. A low pressure cutoff switch was also installed in the inlet line to protect the pump.

The reverse osmosis system was designed using a permeation coefficient of 2.22×10^{-5} grams per square centimeter-second-atmosphere (gm/cm² - sec-atm) for fresh water and 1.25×10^{-5} gm/cm² - sec-atm for sea water. Production of 600 gph on freshwater and 400 gph on sea water was based on an operating pressure of 600 psig and 1000 psig, respectively, using 1320 square feet of membrane. The solids in the fourth pressure vessel were predicted to reach 48,000 mg/l based upon a 27 per cent recovery, and the concentration polarization was estimated to be between 1.03 and 1.06. A channel velocity in the first element was estimated at 1.85 feet per sec (ft/sec) which is high for a spiral-wound element. Although the velocity was high; it was decided to put the four pressure vessels in series.

Three thousand gallons of storage was provided to permit thirty minutes contact time for disinfection. The storage consists of two, 1500 gallon rubber stave tanks connected in series. The requirement to fill a 400 gallon water trailer within 15 minutes was met by using a high volume-low head centrifugal pump.

In the case of chemical and radiological contamination, granular carbon and mixed-bed ion exchange columns were designed as a post-treatment to the reverse osmosis process. The design of these columns were based upon laboratory data and use of Bohart and Adams⁽²⁾ equation. After screening twelve different carbons, it was found that North American G-107 carbon exhibited the best combination of kinetic and equilibria characteristics for removal of chemical agents. Therefore, a fiberglass column containing 70 pounds of this carbon was designed. This provides a three-day operational capacity with a safety factor of two. A similar column containing a mixed bed ion exchange resin was designed for the removal of radioactive contaminants.

Results and Discussion of Equipment Testing

The testing of the equipment was divided into four phases which were (1) component testing, (2) contractor testing, (3) developmental

testing, , and (4) operational testing. Component testing consisted of verifying manufacturers' specifications during the design and fabrication phase of the project. One-hundred hours of contractor acceptance testing was performed to verify the operability of the various processes. The development test, which was 1800 hours in duration, was used to obtain engineering data and maintainability data. Operational testing was used to evaluate the soldier's ability to operate and maintain this equipment in a combat environment.

During the component testing all of the proposed pumps were tested and found to meet required specifications, except for the backwash pump. The impeller diameter in this pump had to be increased from 5 1/2 inches to 6 1/8 inches to get the required flows and head. This change also required increasing the motor size from 5 to 10 horsepower. The only other problem was that a special aramid fiber packing had to be used in the high pressure pump to prevent scoring of the plungers.

Testing of the multi-media filter showed that a five (5) psi head loss through the filter occurred in approximately eight hours. The mean suspended solids removal, as shown in Table II was 83 ± 19.5 percent and this removal seemed independent, of the polymer dosage which was varied between 2.5 and 6 mg/l. Filter runs all exhibited a typical conditioning period with a gradual decrease in solids and turbidity in the effluent. After the minimum point was reached, then a gradual breakthrough was observed, as indicated in Figure 3.

As indicated by the data, the quality of the filtrate was less sensitive to polymer dose than expected. Therefore, for field operations a maximum dosage of 5 mg/l was set regardless of quality of the raw water. This was recognized as risky procedure, however, it was effective for the various waters tested.

Transient analysis showed that the response time to changes in polymer dose was approximately one minute. The rate of change and lag of this response also seems independent of the polymer dose.

Figure 4 shows the results of suspended solids removal from the filter during backwash. Compensating for flow and integrating the data, it was estimated that the filter retained approximately 3300 grams, or 7.25 pounds of solids. Repetitive testing showed that, by using two backwash cycles of 15 and 24 gallons per square foot per minute, the filter was cleaned sufficiently that an initial head loss of 2 psig was always obtained.

Cartridge filters, which ranged in sizes from 3 microns to 20 microns, were tested. The smaller the pore size, the higher the quality of water; however, a trade off had to be made. Data showed that a 5 micron filter produced a water with an effluent quality of less than 0.5 FTU's turbidity and still had an average useful life of seventy-two hours per cartridge filter.

During the 2000 hours of developmental and operational testing the equipment had an average production rate of 610 gallons per hour (gph) on fresh water, 619 gpm on brackish water, and 502 gph on sea water.

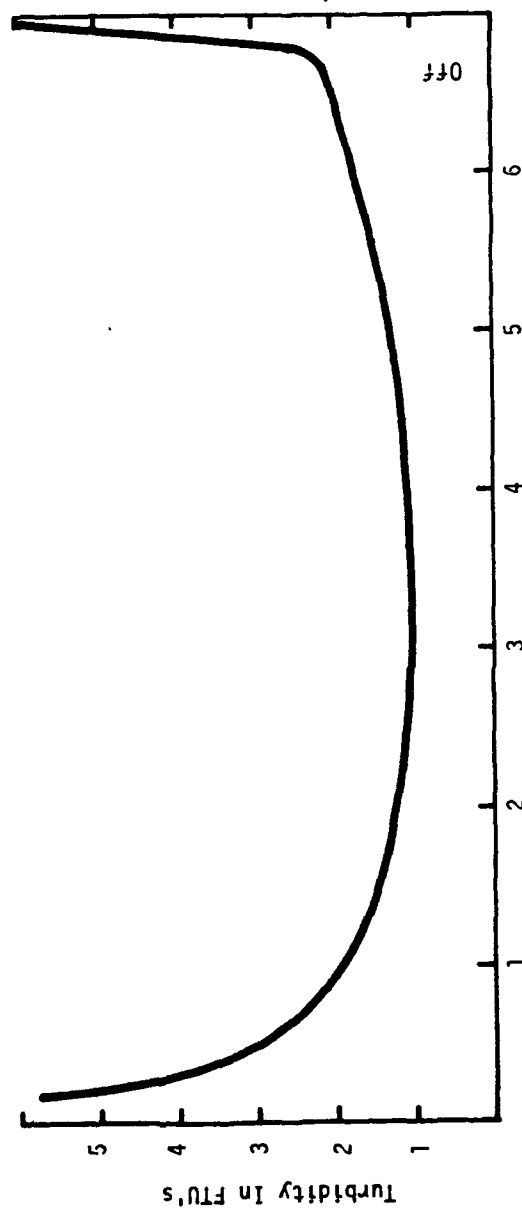


FIG. 3 Typical Breakthrough Curve For Multi-Media Filter

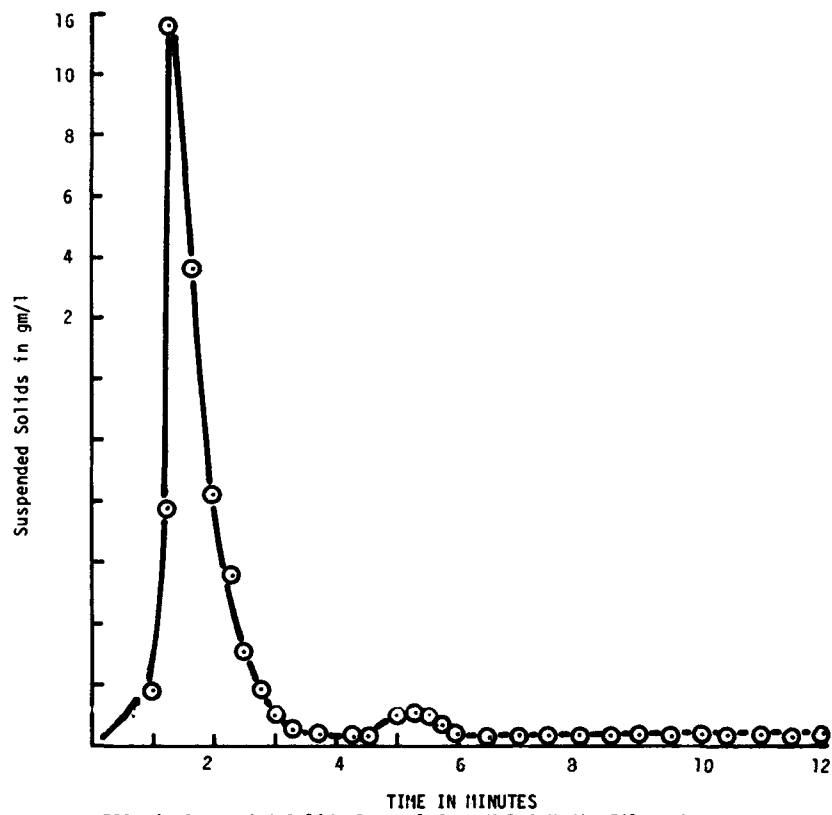


FIG. 4 Suspended Solids Removal From Multi-Media Filter During Backwash

Table II - Results of Component Test of Multi-Media Filter

	Cationic Polymer Dose mg/l	Suspended Solids			Turbidity		
		Influent mg/l	Effluent mg/l	Removal %	Influent (FTU)	Effluent (FTU)	Removal %
4 May	2.5	26	1.7	93	12	0.3	98
8 May	2.5	11	0.8	93	9.6	0.6	94
9 May	2.5	41	1.0	98	22	1.4	94
10 May	2.5	29	1.0	97	14	1.1	92
11 May	4.0	11	1.0	91	12	1.2	91
12 May	4.0	13	2.0	85	10	0.9	91
15 May	4.0	17.6			15	0.9	94
16 May	4.0	39	1.6	96	27	1.8	93
17 May	6.0	42	0.8	98	31	1.6	95
18 May	6.0	76	17	78	49	12	75
23 May	5.0	25.8	0.12	96	21	0.4	98
24 May	5.0	23.2	0.1	99	19	0.7	96
14 Jun	5.0	78.4	8.0	90	16	.2	99

The units availability for water production was 91.4 percent of the time with a mean time between failures of the system, including the generator, of 223 hours. A failure was defined as any unscheduled maintenance requiring more than one hour to repair or repairs beyond the operator's capability. The water purification equipment less generator had a mean time between failure of 501 hours, indicating that the equipment was very reliable.

Table III contains typical reverse osmosis data from the development (DT) and operational (OT) testing. The membranes had higher permeation rates, - 2.94×10^{-5} gm/cm² - atm-sec for freshwater and 1.69×10^{-5} gm/cm² - atm-sec for sea water - than used in the design by 32 and 35 percent respectively. Because of the higher membrane flux, one unit was operated for twelve hours at 792 gph and then for six hours at 1028

Table III
Reverse Osmosis Data
DT/OT Testing (3, 4)

Source	Date:	Total Dissolved Solids		Gallons Per Hour	Flow	Pressure	Hours
		Influent	Product	Influent	Brine		
Fresh	8 Aug	227	3	2040	1440	250 190	24
Fresh	9 Aug	229	4	2040	1440	262 190	24
Fresh	10 Aug	217	3	2040	1410	275 190	24
Fresh	11 Aug	235	5	2040	1440	275 190	24
Fresh	12 Aug	260	3	2040	1440	240 181	24
Fresh	13 Aug	270	3	2040	1440	250 190	24
Fresh	4-5 Oct	115	10	2040	1380	— —	23.5
Brackish	1 Nov	6000	400	2040	1541	460 350	19.50
Brackish	1-2 Nov	5500	150	2040	488	— —	9.75
Sea Water	1 Nov	23560	1200	2040	1248	700 630	11.75
Sea Water	1-2 Nov	22036	900	2040	1012	780 685	6.0
Sea Water	3-4 Nov	22100	1500	2240	1828	— —	18.0
Sea Water	3 Nov	22500	1100	2040	1200	840 770	12.5
Sea Water	6-7 Nov	33050	1200	2040	1645	950 860	10.

gph. This demonstrated that the system could be operated in emergencies at recovery rates as high as 57 percent without seriously effecting the membrane's performance. Based upon this and other data collected, operating at 50 percent recovery for a sustained period should not seriously effect the membrane.

The structure and nomenclature of the three chemical contaminants used in treatment tests of chemically contaminated water in Table IV. The agents GB, and VX are organophosphate compounds similar to malathion and parathion. Due to its low molecular weight GB was predictably the most difficult agent to remove by reverse osmosis as shown in Table V. Clearly the polyamide membrane was superior to the cellulose acetate membrane; however, neither membrane produced an acceptable water when the source was contaminated with GB. Therefore, an activated carbon column was designed and used as a posttreatment process. A laboratory study was conducted which showed that North American G-107 was the optimum carbon. Tracer studies of the carbon column showed that the mean residence time in the column was only one and a half minute; for this reason, the kinetic data was weighted more heavily than the equilibria data in the selection of the carbon.

Studies were also conducted on removal of iodine 131, strontium 85, and cesium 134 by reverse osmosis. The equipment as shown in Table VI successfully removed the isotopes, but not to acceptable levels. As in the case with the chemical contamination, a posttreatment column using a mixed-bed ion exchange resin had to be used. A column similar to that used for the chemical agent was used. Similar problems were observed; the short contact time and low concentration driving force made both the ion exchange and adsorption systems inefficient, but reliable treatment processes.

Conclusions

Reverse osmosis is an effective process for treating sea, brackish and chemically contaminated fresh water.

Permeation coefficients of 2.22×10^{-5} and 1.25×10^{-5} gm/cm² - atm-sec are realistic design parameters for freshwater and sea water sources, respectively.

A recovery as high as 50 per cent can be obtained with no immediate detrimental effect to spiral wound membranes.

Chemical and radiological contaminants can be removed by reverse osmosis, but posttreatment with carbon adsorption and ion exchange columns is required to produce potable water.

Direct filtration using in-line addition of cationic polymer followed by a 5 micron cartridge filter is adequate pretreatment for the reverse osmosis system.

Positive displacement pumps are an effective means of controlling the flow within the system regardless of pressure.

TABLE IV
NOMENCLATURE AND STRUCTURE OF
CHEMICAL CONTAMINANTS

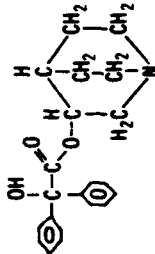
AGENT	FORMULA
GB Isopropylmethylphosphonofluoridate	$ \begin{array}{c} \text{CH}_3 \\ \\ \text{H}_3\text{C}-\text{P}-\text{O}-\text{C}-\text{H} \\ \quad \\ \text{F} \quad \text{O} \\ \text{O} \end{array} $
VX O-ethyl S-(2-diisopropylaminoethyl) methylphosphonothioate	$ \begin{array}{c} \text{OC}_2\text{H}_5 \\ \\ \text{H}_3\text{C}-\text{P}-\text{S}-\text{CH}_2\text{CH}_2\text{N} \\ \quad \\ \text{O} \quad \text{C} \\ \text{O} \quad \\ \text{O} \quad \text{C}-\text{CH}_3 \\ \quad \\ \text{H} \quad \text{H} \\ \text{C} \quad \text{C} \\ \quad \\ \text{H}_3 \quad \text{H}_3 \end{array} $
BZ 3-Quinuclidinyl Benzilate	

TABLE V - Removal of Chemical Contaminants From Freshwater By Reverse Osmosis

Agent	MPC* mg/l	Raw Water mg/l	Agent Concentration In Product mg/l		Agent Concentration After Carbon Adsorption	
			With Chlorination Cellulose Polyamide Acetate	Without Chlorination Cellulose Polyamide Acetate	Cellulose Acetate	Polyamide
GB	0.02	7.54	5.12	0.067	5.74	0.074
VX	0.02	10.14	0.217	0.0086	—	—
BZ	0.007	6.95	1.79	0.005	1.15	0.006
					0.0006	0.0005
					0.0001	0.0001
					0.003	0.002

TABLE VI - Removal of Radioactive Material From Freshwater By Reverse Osmosis

Agent	MPC pci/l	Raw Water pci/l	Agent Concentration pci/l		Recovery %		Flux	
			Cellulose Acetate	Polyamide	Cellulose Acetate	Polyamide	Cellulose Acetate	Polyamide
¹³¹ I	300	297000	19400	13300	25	27	21	22
⁸⁵ Sr	300	322000	3430	830	25	26	22	22
¹³⁴ Cs	9000	173000	17700	2030	25	24	21	20

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Acknowledgement

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